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Using a pulsed laser beam to investigate the feasibility of sub-pixel position resolution with time-correlated transient signals in 3D pixelated CdZnTe detectors

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Abstract— We evaluated the X-Y position resolution achievable in 3D pixelated detectors by processing the signal waveforms readout from neighboring pixels. In these measurements we used a focused light beam, down to 10 μm , generated by a ~1 mW pulsed laser (650 nm) to carry out raster scans over selected 3x3 pixel areas, while recording the charge signals from the 9 pixels and the cathode using two synchronized digital oscilloscopes.

Keywords: CdZnTe, High-granularity detectors, 3D pixelated detectors, Crystal defects, Charge sharing, Charge-loss correction

1. Introduction

Crystal defects are a major problem causing response non-uniformity of CdZnTe (CZT) detectors. To address this challenge, high-granularity position-sensitive detectors have been proposed to correct response non-uniformity by virtually dividing the detectors volumes into small voxels and equalizing the responses from each voxel [1-4]. Previously, we demonstrated the feasibility of this approach for position-sensitive virtual Frisch-grid detectors, which allowed us to achieve high detection performance, while using unselected typical-grade CZT crystals available at lesser cost. We also demonstrated the feasibility of the response corrections using charge sharing for 3D pixelated detectors with small-pixel sizes, <1 mm [5]. However, the response corrections based on high-granularity position sensing have not yet been demonstrated for pixelated detectors with large-pixel sizes for which the charge sharing events are only a small fraction.

3D pixelated detectors offer many capabilities in signal processing and enhancing the detector performance [5-6]. However, today, 3D large-volume pixelated detectors still rely on using the highest quality CZT crystals, which makes them expensive and often not readily available for many practical applications. Enabling 3D detectors to correct for response non-uniformity caused by crystal defects requires high position resolution on the order of ~100 μm or better in the X-Y directions. The recently reported position resolution of 3D pixelated detectors is 330 μm [7] at 662 keV, which in many cases is not sufficient for correcting response non-uniformities.

Two approaches have been tried in the past to enhance the spatial resolution in pixelated detectors by using single-pixel events and charge-sharing events [7-11]. The first approach is applied when the whole charge from the electron cloud is collected on a single pixel [10-11]. In such cases, the electron cloud induces transient signals on the surrounding pixels with well-defined peaks, where the amplitudes of the transient signals can be converted into X-Y coordinates of interaction points. The signal generated on the central pixel cannot be used, because its amplitude is not sensitive to position within the central pixel. The main drawback of this method is that the signals induced on neighboring pixels are rather weak. In addition, a strong electrostatic shielding by the central pixel reduces the sensitivity of the non-collecting neighboring pixels to the locations of the electron clouds.

The second approach is applied when the total charge from the electron cloud is shared between two or more neighboring pixels (charge-sharing events). As in the previous approach, the signal amplitudes corresponding to these pixels can be used to refine the positions of the interaction points with accuracy better than the pixel size. The principal difference between these two approaches is that in the first case, the amplitudes of the induced signals (pixel response functions) are represented by a complex function of X-Y-Z coordinates, while in the second case, the amounts of collected charges are described by linear functions of X-Y coordinates only. Moreover, in the first case the sum of the induced amplitudes at any fixed Z (or time) is not equal to the total charge (weakly correlated), while in the second case, the sum of the collected charges is always equal to the total charge (fully correlated signals). Since, in the case of charge sharing, the measured amplitudes are fully correlated, the center of gravity formulas provide the highest accuracy for the X-Y coordinates:

$$X = \frac{A_x^1}{A_x^2 + A_x^1} \quad (1)$$

$$Y = \frac{A_y^1}{A_y^2 + A_y^1}, \quad (2)$$

where A_x and A_y represent amounts of the collected charges from the 4 cardinal pixels: right-left and top-bottom. In the first case of the induced signal approach, the actual pixel response functions have to be used to evaluate the X-Y coordinates of the electron cloud. Moreover, to achieve the best resolution in this case, it is crucial to use time-correlated amplitudes, such as those available from the digitized signals (waveforms) captured from the adjacent neighboring pixels.

As mentioned, the charge-sharing approach allows for achieving high position resolution, $<100 \mu\text{m}$, but it relies on using small size pixels, which is not practical for large-volume CZT detectors, since it would require a large number of readout channels. However, based on consideration of the electronics design and data processing, it is more practical to use large pixels to minimize a fraction of the charge-sharing events and reduce the number of readout channels, which forces detector developers to use the transient-signal approach for achieving sub-pixel sensitivity. On the other hand, increasing a pixel size will eventually start hurting the detector's spectral and position resolutions.

Both single-charge and charge-sharing events occur in pixelated detectors with the number of shared events increasing as the pixel size decreases. This means that both approaches should be combined to evaluate the coordinates of the interaction points in pixelated detectors.

The principal goal of this work is to evaluate sub-pixel position resolution of a 3D pixelated detector with a pixel size of $1.72 \times 1.72 \text{ mm}^2$ and demonstrate the advantage of using time-correlated signals for enhancing the position resolution. In this study, we considered the single-point interaction events only which were generated by means of the pulsed laser. Although a pulsed laser beam does not substitute gamma-ray charge clouds, in some cases it can be used to "model" the interaction events. For the energy calibration we used a real ^{137}Cs source. This work excludes the effects related to the variations of the electron cloud sizes and depth of the interactions. However, the effects of broadening of the electron clouds due to diffusion and electronic noise were taken into account.

We investigated position resolution of a commercial $20 \times 20 \times 10 \text{ mm}^3$ pixelated detector with a standard 11×11 pattern of 1.72 mm -size pixels (1.22 mm contact size, 0.5 mm gaps between the contacts, and without the interposing grid) to investigate the usage of generated signals on neighboring pixels to measure the positions of the interaction points.

2. EXPERIMENTAL SETUP

The pulsed laser beam system is comprised of a 1 mW laser (650 nm wavelength) coupled with a single mode optical fiber ($9 \mu\text{m}$) to the microscope objective. The beam is manually focused on the surface of the detector over the pixels of interest using focal lenses as shown on Fig. 1. Use of the laser beam for testing CZT detectors cannot entirely substitute for actual gamma-ray excitation, but it has several advantages for the measurements conducted in this study. It provides precise timing and location information of the originally generated charge, and it is capable of generating stronger signals to minimize contributions from electronic noise.

The detector was plugged into the motherboard inside a test box containing 10 ultra-low-noise charge-sensitive preamplifiers (eV-5093), whose inputs were connected to the pixels of interest in the detector. The test box was secured on X-Y translation stages controlled by a computer program.

The pixelated detectors were acquired from Redlen Technologies Inc., as low-grade (rejected previously by other customers) detectors with a minimum area of 3×3 working pixels. The pixel size is 1.72 mm . Fig. 2 visually illustrates the position of the $100 \mu\text{m}$ (unfocused to make it visible to the naked eye) beam on the surface of a $20 \times 20 \times 5 \text{ mm}^3$ pixelated CZT detector. All the 121 pixel pin connectors have matching sockets in the readout electronics' box board underneath, allowing the selection and amplification of individual pixels. The high-voltage settings were 650 V and 1000 V for the $20 \times 20 \times 5 \text{ mm}^3$ and $20 \times 20 \times 10 \text{ mm}^3$ detectors respectively.

Fig. 1. Pulsed laser beam set up with the detector box open showing a 20x20x5 mm³ pixelated CZT detector. The optic fiber is attached from the laser output to the top of the lenses.

The signals from the nine pixels plus the cathode were recorded using two synchronized oscilloscopes: LeCroy HDO 8058 oscilloscope and a LeCroy 6050 Waverunner. The signals, generated by locally creating carriers near the cathode, were sampled with 10-ns time intervals (bins) and stored in the oscilloscopes' memories for further analysis. Fig. 3(a) shows an example of the 9 digitized waveforms generated by the laser pulses equivalent to the deposited energy of ~600 keV. In this example, the total charge is shared between the top and central pixels with most of the charge collected on the central pixel.

Fig. 2. Continuous laser beam (100 µm) focused on the surface of a 20x20x5 mm³ pixelated CZT detector. The cathode signal is connected to a charge-sensitive preamplifier.

We developed an automated system to take measurements by moving the laser beam at small steps, typically 20 µm, across the central pixel in horizontal and vertical lines. The 3x3 areas of interest (a central pixel and its 8 surrounding neighbors) were selected based on the performance criteria and the least electronic noise. The laser remained at 1 mW while the pulse width was within the range of 17-92 ns depending on the deposited energy being evaluated. We also took data with the uncollimated ¹³⁷Cs source which we used for calibrating the energy of the laser-generated pulses and illustrating the sub-pixel imaging capability. For these measurements, we selected only single-point interaction events.

Fig. 3. (a) Inverted cathode signal with solid a line indicating the starting moment. (b) Waveforms from the central pixel and its surrounding neighbors showing a charge-sharing interaction between the top pixel and central pixels with a majority of the charge collected on the central pixel. The vertical solid lines indicate a trigger signal generated by the laser (starting moment of the charge signal). The dashed line in the central-pixel plot represents the moment when the electron cloud is collected on the pixel. (c) The added signals from 3 pixels aligned in the X and Y directions are explained in the data analysis section. The vertical lines display the moment when the electron cloud was collected on the central pixel.

3. Data Analysis

As was pointed out above, the laser provides a trigger signal to identify event starting times (the beginnings of the charge signals). For each event, we captured 10 waveforms of all 9 pixels (a central pixel plus 8 neighbors) and the cathode. As a first step, we apply the third-order Savitzky-Golay filter with 16 data points [12] to smooth the captured waveforms. We then identify a pixel with the highest amplitude and use its waveform to evaluate the moment when the electron cloud reaches the anode as a crossing point of the two fitting lines as illustrated in Fig. 3(a) [13]. For the majority of our scans, we ensured that this was the central pixel. After this moment all the waveforms must plateau out at either a zero level, meaning that no charge has been collected at these pixels, or at some positive levels proportional to the collected charges (charge sharing). Using these levels we can identify the charge-sharing events and the pixels onto which the charges were actually collected. We note that the main advantage of using the waveform digitizing readout electronics for reading signals in pixelated detectors is an ability to use these levels for identifying the single pixel and charge-sharing events. In our measurements, we used these levels to identify the actual physical boundaries between the neighboring pixels (typically in CZT detectors suffering from the local variations of the electric field, the actual boundaries can be different from the geometrical ones defined by the pixel contacts). When the interaction point is located over the actual boundary between two pixels, the levels measured from these pixels should be equal.

After verifying that an event belongs to the central pixel (its signal must have the highest level), the signals from the neighboring pixels can be used to refine the position of the interaction point.

Perhaps, the most reliable and accurate way for identifying the location of the interaction point is to use the entire waveforms and the maximum-likelihood method to find the best fit to the benchmark waveforms obtained from calibration or simulated theoretically [14]. Although very powerful, this approach requires very laborious calibrations and its practical usage in the case of pixelated detectors with multiple interaction events is still questionable. In this work, we limit ourselves to using just one sample from each waveform to evaluate the X-Y coordinates.

There are several possibilities for choosing the samples to evaluate the X-Y coordinates. For example, we can use the samples corresponding to the maxima of the transient signals (the origin of this approach comes from using analog shaping filters and peak detectors to measure signal amplitudes.) The advantage of this approach is that it maximizes the signal-to-noise ratio for the selected samples. However, in this case, the selected samples are not time correlated, which increases the statistical and systematic errors. As a result, the overall performance of this particular estimator may not be the best option.

In this work, we compared three options (or estimators if employing the terminology used in statistical analysis) for selecting the waveform samples. The first estimator, referred to as the slice technique, relies on slicing the waveform by selecting a fixed time-bin corresponding to a 2-mm distance from the anode (the time bin right before any of the transient signals reach their maxima). The second estimator uses samples corresponding to the maxima of the transient signal as previously explained. The third estimator evaluated is explained in the following paragraphs and is referred to as the time-correlated samples technique.

Fig. 3 schematically shows the 3x3 area of the detector, while A_i represents the sample amplitude (as described above) selected from the transient signals captured from the 9 peripheral pixels. In general, each A_i is a function of the location of the electron cloud (X, Y, Z) (or time, T , which is equivalent to the Z coordinate). However, if we select time-correlated amplitudes we eliminate dependence on Z . Furthermore, we add together signals from 3 pixels aligned in the X and Y directions as illustrated in Fig. 4. The main reason for doing this is to make A_i mainly dependable on one coordinate X or Y (at least in the first approximation). We called A_i response functions of the adjacent pixels, R .

Fig. 4. Identification of pixel amplitudes summed to use in the response function approach. Each of the 4 summed amplitudes gives an estimate for the X and Y positions.

If the response of the functions are known we can generate two estimates for the X coordinates and two estimates for the Y coordinates:

$$X_1 = R^{-1}(A_x^1) \quad (3)$$

$$X_2 = L - R^{-1}(A_x^2) \quad (4)$$

$$Y_1 = R^{-1}(A_y^1) \quad (5)$$

$$Y_2 = L - R^{-1}(A_y^2), \quad (6)$$

where R^{-1} is the reverse response function, and L is the distance between pixels. We excluded the estimates that can be generated using the central pixels because of the strong correlations of the response function. If used, the third estimate would not be independent. As shown next, the response functions associated with the central pixels have the weakest sensitivity to the positions.

Ideally, all the response functions are identical and can be calculated numerically. In reality, however, they could be affected by the electric field non-uniformity and have to be calibrated for each pixel. Alternatively, we can use the identical response functions for all pixels and apply geometrical corrections for each pixel individually.

The two estimates for X and Y can be combined using a weighted average method. The weights are normally defined as inversely proportional to the variances: $W = \frac{1}{\sigma_x^2}$ where $\sigma_x^2 = \left(\frac{\partial R}{\partial A}\right)^2 \sigma_A^2$. Good approximations for the weights are given by the amplitudes of measured signals:

$$X = \frac{X_1 W_1 + X_2 W_2}{W_1 + W_2} = \frac{R^{-1}(A_x^1) A_x^1 + (L - R^{-1}(A_x^2)) A_x^2}{A_x^1 + A_x^2} \quad (7)$$

$$Y = \frac{Y_1 W_1 + Y_2 W_2}{W_1 + W_2} = \frac{R^{-1}(A_y^1) A_y^1 + (L - R^{-1}(A_y^2)) A_y^2}{A_y^1 + A_y^2} \quad (8)$$

In the above equations, we treat the third coordinate (time) as a parameter. Selecting the waveforms samples at different times, we can trace the electron cloud's positions in a 3D space.

The 3-dimensional response functions can be evaluated numerically by propagating the continuously expanding electron cloud due to diffusion and electrostatic repulsion in a uniform electric field. Z dependences of the response functions (at fixed values for X and Y) represent the charge signals (waveforms) expected from the pixels as the electron cloud drifts from a particular location defined by its X - Y coordinates towards the anodes. The response functions can also be plotted as a 1-dimensional function of X (or Y) at fixed Z and Y (or X). Fig. 5 shows relative dependences of the induced charges on three aligned pixels versus X coordinates at the fixed Y and Z coordinates (in this case we put $Y=0$) calculated for 1.72-mm size pixels. Each plot shows the identical responses functions shifted by 1.72 mm for the three estimators. The gray areas in the

middle of each plot represent the central pixel regions (areas of interest). The sum of three functions is close to a constant, meaning that the three functions are correlated, and only two of them can be used to evaluate the X coordinate. It is clear that the response function of the central pixel is the least sensitive to the X coordinates. That is why in Eqs. (3-6) we use only two estimates based on the signals generated on the left and right pixels only to evaluate the X coordinate. The same is applied to the

The three plots in Fig. 5 correspond to the three options for choosing the Z coordinate, which we compare in this work. Plot 5(a) shows the response functions calculated at the Z coordinate corresponding to 2-mm distance from the anode. If we convert this distance into the drift time of the actual measured waveforms (shown in Fig. 3), it will correspond to the time bin right before any of the transient signals reach their maxima. The difference between the highest and lowest values of the response function at the pixel boundary is the range in which the response function varies as the location of the interaction point shifts from one boundary to another. This range is directly related to the accuracy of the position measurement.

Fig. 5. Theoretical response function models with amplitude transient signals dependence for all three estimators evaluated as 1-dimensional functions.

Fig. 5(b) illustrates the second option of choosing Z coordinates, corresponding to the maximum values of response function. Again, if we convert these distances into the drift times of the waveforms shown in Fig. 3, they will correspond to the time bins when the transient signals reach their maximum, which is an advantage with respect to the signal-to-noise ratio. However, the samples are not time-correlated, which can add more uncertainties. As seen from the plot 5(b), this option gives a higher variation range compared to the previous case.

Lastly, the plot 5(c) shows the third option, the time correlated samples technique. In this case, we selected Z coordinates corresponding to the maximum of two response functions: on the left and on the right. In the waveforms shown in Fig. 3, this corresponds to the time bin when the strongest signal reaches its maximum. In this case we use the time-correlated samples, and at least one of the two samples has the highest amplitude (maximum signal-to-noise ratio).

205 In a first approximation, the R can be described by a linear function: $R=a+bX$ (or $R=a+bY$). If we use the normalized amplitudes A_x^1 and A_x^2 whose values vary between 0 and 1, then we can write X and Y as:

$$X = LA_x^1 \quad (9)$$

$$X = L(1 - A_x^2) \quad (10)$$

210 Substituting these equations into (7) and (8), we get simple estimators for the X and Y coordinates:

$$X = \frac{A_x^1}{A_x^1 + A_x^2} \quad (11)$$

$$Y = \frac{A_y^1}{A_y^1 + A_y^2} \quad (12)$$

215 For each coordinate, we selected two time-correlated samples: A_x^1 and A_x^2 for X and A_y^1 and A_y^2 for Y from the corresponding waveforms. Each pair was selected at a time at which the sample was the highest. In other words, one of A_x^1 and A_x^2 (and similarly of A_y^1 and A_y^2) is the maximum sample of the two corresponding waveforms. By selecting the highest amplitude and time-correlated samples, we minimize the statistical (electronic) noise. As seen from Fig. 5, the third option gives the highest variation range, so we can expect to achieve the best position resolution by using the time correlated samples technique.

220 The calibration procedure consisted of first locating the central pixel and then the middle points for each of the four corner pixels by using the oscilloscope to compare the amplitudes of the signals captured from these pixels. The actual criteria we used to find pixel boundaries uses equal amplitudes of the signals readout from two adjacent pixels (equal-charge-sharing criteria). The scan boundaries are defined by connecting the corner middle points allowing us to carry out two linear scans across the central pixel along the X and Y directions. For each beam position we captured 1000 waveforms and plotted 225 distributions of the selected samples A_x^1 , A_x^2 , A_y^1 and A_y^2 which then were converted into XY positions measured in relative units.

The evaluated distributions of XY were plotted in the relative unit coordinate system which could be related to the actual geometrical locations of the laser beam. Using the equal-charge-sharing criteria we could identify the points in the relative unit coordinate system corresponding to the pixel boundaries. This allowed us to calibrate our measurements: find a relationship 230 between the relative units and pixel geometrical dimensions.

Next, we evaluated their mean values using Gaussian fits. Then we identified the beam locations corresponding to the central pixel boundaries by comparing the levels of the corresponding waveforms. When the beam moves up between two pixel boundaries, the mean of A_x^1 distributions varies from its minimum to its maximum value, while the mean of A_x^2 distribution varies from its maximum to its minimum. Accordingly, when a beam moves from left to right, the mean values of A_y^1 and A_y^2 distributions undergo similar changes.

235 As we mentioned above, use of the linear approximation resulted in slight geometrical distortions (systematic errors) near the pixel edges. Knowing the number of steps and their size allowed calculating the location of the laser beam relative to the center of the pixel creating a relative unit coordinate system. Normally, the pixel boundary in relative units is not always exactly a square due to the local electric field non-uniformities. However, in these measurements we try to select uniform pixels. For calibration, to reduce the systematic errors due to use of the linear approximation of the response functions, we chose the laser 240 beam positions two steps after and before from the geometrical pixel edges.

4. Results and Discussion

Two major factors can affect position resolution: electronic noise and systematic errors caused by using an approximated response function. Since the latter effect (which gives rise to large-scale geometrical distortion) can be fully corrected by using 245 calibration data, our primary interest is to evaluate the statistical errors due to electronic noise.

The electronic noise of our readout electronics was evaluated by plotting variations of the waveform baselines after applying the Savitzky-Golay filter. We used a sample corresponding to a bin before the time stamp of the event of every waveform to measure the distributions of the baseline variations for each readout channel. Using the Gaussian fits of the measured distributions, we found the FWHM electronic noise to be in the range 4-5 keV (i.e., the statistical error for the measured samples 250 after adding together three waveforms).

As explained earlier, the captured waveforms help identify the moment when the electron cloud reaches the anode, charge sharing events and pixels onto which the charges were actually collected. This information can also help to identify the physical boundaries between neighboring pixels, which is used to evaluate and differentiate both events to improve position resolution. Fig. 6 presents this evaluation of position interactions using a linear approximation for the response function; it displays 255 the approximate central pixel area. The solid-line squares display the beam boundaries, $1.52 \times 1.52 \text{ mm}^2$, used for the response function normalization and spatial calibration (one step before each pixel edge). The boundaries between charge sharing and single-pixel events, $1.02 \times 1.02 \text{ mm}^2$, are marked by the dashed lines. The non-linear response is caused by a non-uniform electric field.

Fig. 6. Position resolution evaluation using a linear approximation for the response function. The line width gives the position resolution, which is estimated to be $<50 \mu\text{m}$ at an energy of approximately 2 MeV. The outer square represents the pixel area of $1.52 \times 1.52 \text{ mm}^2$ (minus 2 10-mm steps) identified based on the charge sharing signals amplitudes. The internal square represents the area of $1.02 \times 1.02 \text{ mm}^2$ corresponding to the single pixel events identified based on the signal levels (see the text for details).

Evaluating position resolution of the experimental linear scans with the pulsed laser system in the cardinal directions yielded an estimated position resolution of approximately $50 \mu\text{m}$ at an energy equivalent to 2 MeV. Another example of this evaluation is shown in Fig. 7 carried out with energy of approximately 260 keV and yielding a position resolution of close to $200 \mu\text{m}$.

Fig. 7. Same position resolution evaluation as Fig. 6, but the gamma energy is approximately 260 keV.

As mentioned in the data analysis section, this work compares three options (estimators) for selecting the waveform samples. A comparison of position resolution using all three estimators is shown in Fig. 8 with energies between 150 keV and 2 MeV. The time correlated samples option has shown higher position resolution compared to the slice and maximum amplitude estimators. The simulations shown in Fig. 5 showed the response function dynamic range for all three estimators, which is directly related to the position measurement accuracy. The lowest range was expected from the slice option, which is in agreement with the experimental data as it has the lowest position resolution of the three options (estimators) evaluated in this work. The maximum amplitude option shows significantly higher experimental results compared to the first option and gives the advantage of better signal-to-noise ratio. All three curves converge at high energies where the effect of the electronic noise becomes negligible. The position resolution of $<50 \mu\text{m}$ evaluated at $\sim 2 \text{ MeV}$ is likely attributed to the uncertainty of the laser beam only. These uncertainties include diffusion, local fluctuations of the electric field caused by crystal defects, and laser instabilities all which affect the position resolution. In the case of actual gamma-rays the resolution is expected to degrade further.

Fig. 8. Position resolution evaluation at various gamma energies for time correlated samples using a 20x20x10 mm³ 3D pixelated detector. Pixel size is 1.72 x 1.72 mm².

To illustrate the effect of using a linear approximation for the response function across the full area of the pixel, we conducted multiple linear scans across all pixels in the 3x3 area. Fig. 9 presents this evaluation and shows a small distortion that can be corrected via pixel calibration. It is also important to note that the electric field in the crystal is not uniform and contributes to this distortion.

Fig. 9. Position resolution evaluated from using raster scans across the detector at an equivalent energy of 2 MeV.

5. Conclusion

Using a focused laser beam, we demonstrated an improvement in sub-pixel position resolution with time-correlated transient signals in pixelated CZT detectors. The < 60 micron pulsed laser beam created carriers near the cathode, generating signals on a 3x3 pixel area of interest, thus allowing the measuring of position interactions including single charge and charge sharing events. To evaluate the position resolution (FWHM), we studied three different options for selecting position for the waveform samples to obtain the best method. Ultimately the time correlated samples approach resulted in the best position resolution, 200 μm for 260 keV and < 50 μm at the energy of 2 MeV with a contribution of the electronic noise (FWHM) of 4-5 keV. We believe that these results can be improved by using a waveform digitizing ASIC [15]. We should note that these results cannot substitute those with gamma-rays and in the latter case the resolution is expected to degrade further.

Although charge sharing provides a better accuracy for the X-Y coordinates, it can be applied only to a small fraction of the charge-sharing events, and only if the boundaries of the charge-sharing region are known. The latter depends on the size of the electron cloud which, in turn, depends on the drift distance. As we demonstrated here, the transient signals allow us to treat both types of events the same way. However, it will require using a more accurate response function or applying geometrical corrections.

Overall, the selection of the time-correlated signal position still requires further evaluation to optimize the amplitude values used and further improve the algorithm. Future analysis of this technique will be performed using detectors with different thicknesses (to allow studying the diffusion and its effect on position resolution) and pixel sizes.

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References

- [1] Z. He, W. Li, G. F. Knoll, D. K. Wehe, J. Berry, and C. M. Stahle, "3-D position sensitive CdZnTe gamma-ray spectrometers," Nucl. Instr. and Meth. A 422, pp. 173-178, 1999.
- [2] M. A. J. van Pamelén and C. Budtz-Jørgensen, "CdZnTe drift detector with correction for hole trapping", Nucl. Instr. and Meth. A 411, pp. 197-200, 1998.
- [3] D. R. Nygren, "A time projection chamber", presented at 1975 PEP Summer Study, PEP 198, 1975 and included in Proceedings.
- [4] G. F. Knoll, Radiation Detection and Measurement, 3rd ed. 2000, New York: John Wiley & Sons, Inc.
- [5] A. E. Bolotnikov, G. S. Camarda, Y. Cui, G. De Geronimo, J. Eger, A. Emerick, J. Fried, A. Hossain, U. Roy, C. Salwen, S. Soldner, E. Vernon, G. Yang and R. B. James, "Use of high-granularity CdZnTe pixelated detectors to correct response non-uniformities caused by defects in crystals," *Nuclear Instruments and Methods in Physics Research A* 805, pp. 41-54, 2016.
- [6] A. E. Bolotnikov, G. S. Camarda, Y. Cui, G. De Geronimo, J. Fried, A. Hossain, K. Lee, G. Mahler, M. Maritato, M. Marshall, M. Petryk, U. Roy, E. Vernon, G. Yang, R. B. James, *Applied Physics Letters* 104 (2014) 263503.
- [7] Y. Zhu, S. Anderson and Z. He, "Sub-Pixel Position Sensing for Pixelated, 3-D Position Sensitive, Wide Band-Gap, Semiconductor, Gamma-Ray Detectors," *IEEE Transactions on Nuclear Science* 58, no. 3, pp. 1400-1409, 2011.
- [8] M. A. J. van Pamelén, C. Budtz-Jørgensen, *Nuclear Instruments and Methods A* 403 (1997) 390.
- [9] I. Kuvvetli, C. Budtz-Jørgensen, E. Caroli, N. Auricchio, *Nuclear Instruments and Methods A* 624 (2010) 486.
- [10] W. Warburton, "An approach to sub-pixel spatial resolution in room temperature X-ray detector arrays with good energy resolution," In: *Proceedings of Materials Research Society Symposium*, 1997, vol. 487, pp. 531-536.
- [11] T. Narita, J. E. Grindlay, J. Hong, F. C. Niemiński, *Proc. SPIE*, Vol. 5165, X-Ray and Gamma-Ray Instrumentation for Astronomy XIII, pp. 542-643, 2004.
- [12] A. Savitzky, M. J. Golay, "Smoothing and Differentiation of Data by Simplified Least Squares Procedures," *Analytical Chemistry* 36 (8), 1627-39, 1964.
- [13] C. M. Hubert Chen, S. E. Boggs, A. E. Bolotnikov, W. R. Cook, F. A. Harrison, and S. M. Schindler, "Numerical Modeling of Charge Sharing in CdZnTe Pixel Detectors", *IEEE Trans. Nucl. Sci.* 49, no. 1, pp. 270-276, 2002.
- [14] G. Montemont, S. Lux, O. Monnet, S. Stanchina, L. Verger, "Studying Spatial Resolution of CZT Detectors Using Sub-Pixel Positioning for SPECT," *IEEE Trans. Nucl. Sci.* 61, no. 5, pp. 2559-2566, 2014.
- [15] M. Streicher, S. Brown, Y. Zhu, D. Goodman, Z. He, "Special Nuclear Material Characterization Using Digital 3-D Position Sensitive CdZnTe Detectors and High Purity Germanium Spectrometers", *IEEE Trans. Nucl. Sci.* 63, no. 5, 2016.